Non-Equilibrium Ionization State and Two-Temperature Structure in the Linked Region of Abell 399/401

...will be submitted to PASJ

@Tsukuba

Takuya Akahori[1†] and Kohji Yoshikawa[1]

[1]*Center for Computational Sciences, University of Tsukuba, Japan*

[†]*a research fellow, akataku@ccs.tsukuba.ac.jp*

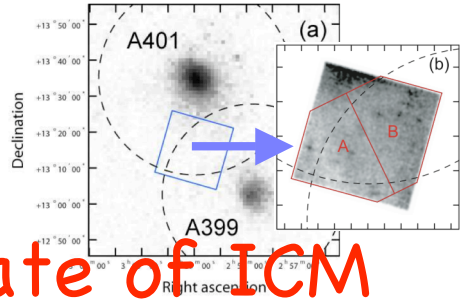
The Warm & Hot Universe

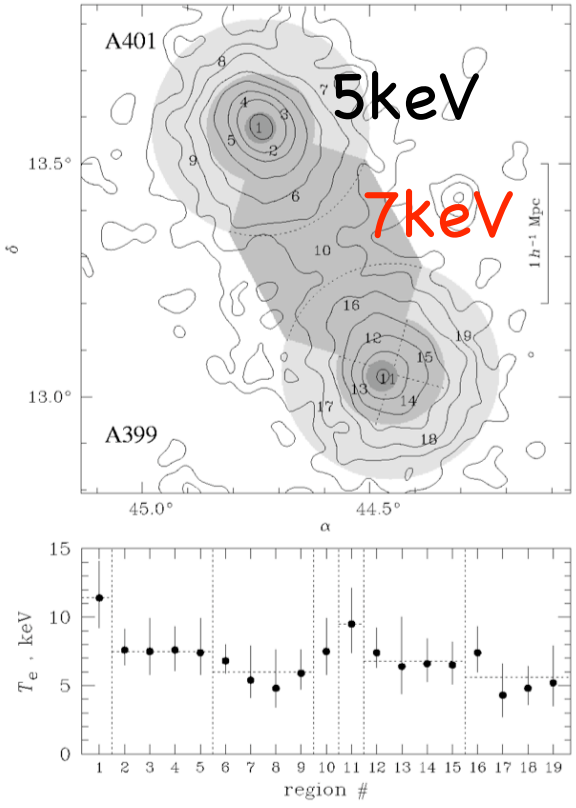
May 7-9, 2008, Columbia University, New York City, USA

1) Introduction to Abell 399/401

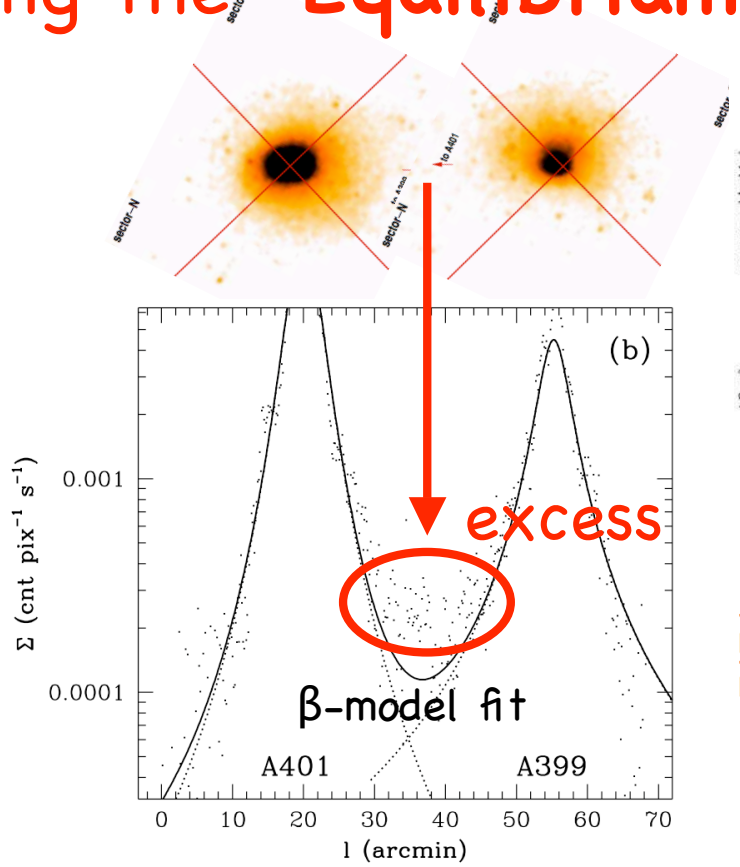
- On an early stage of a **merging**
- **High Metallicity** in the linked region

↑ assuming the "Equilibrium" state of ICM

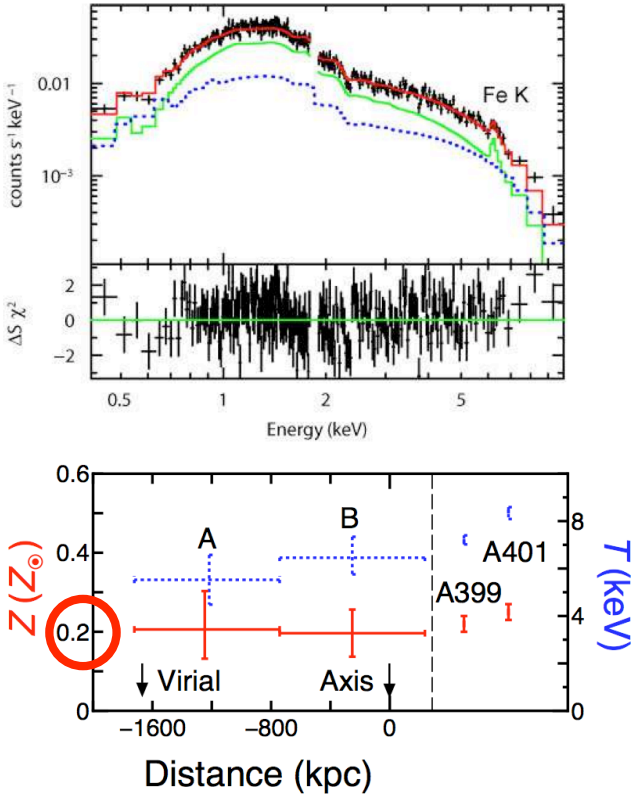




ASCA: Temp. map
Markevitch+ '98



XMM-Newton: Bright. profile
Sakelliou, Ponman '04



Suzaku: Metallicity
Fujita+ '08

2) Equilibrium Timescale

- The linked region → Gas density ~ 10^{-4} (cm^{-3})
  - Timescale of Collisional ionization equilibrium
    - $t_{ion-rec}$ ~ 3×10^{-2} Gyr $(n/10^{-2}cm^{-3})^{-1}$ (e.g., Masai '84)
  - Timescale of e-i temperature equilibration
    - t_{e-i} ~ 2×10^{-2} Gyr $(n/10^{-2}cm^{-3})^{-1}(T/10^{8}K)$ (Spitzer '56)

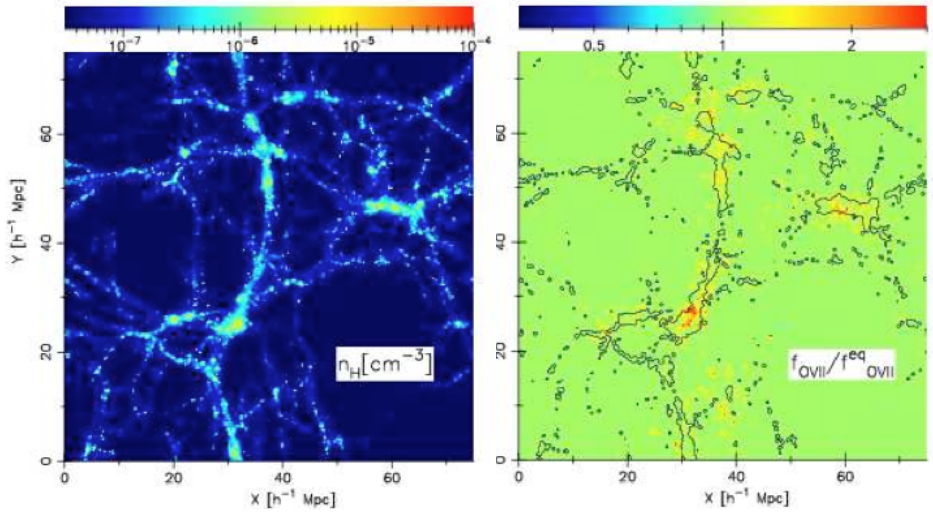
Area · Density (cm^{-3})	Eq. time (Gyr)	Dyn. time (Gyr)	EQ?
Center ~10^{-2}	~10^{-2}	~1	○
Outskirts ~10^{-4}	~1	~1	△
Shock ~10^{-2}	~10^{-2}	~10^{-2*}	△

*Sound crossing time through 10 kpc

"Equilibrium" is not always a reasonable assumption at the outskirts of clusters!!

3) Motivation

- Actually, in the warm-hot intergalactic medium (**WHIM**), where the density is lower, a non-EQ state or 2T structure have been pointed out

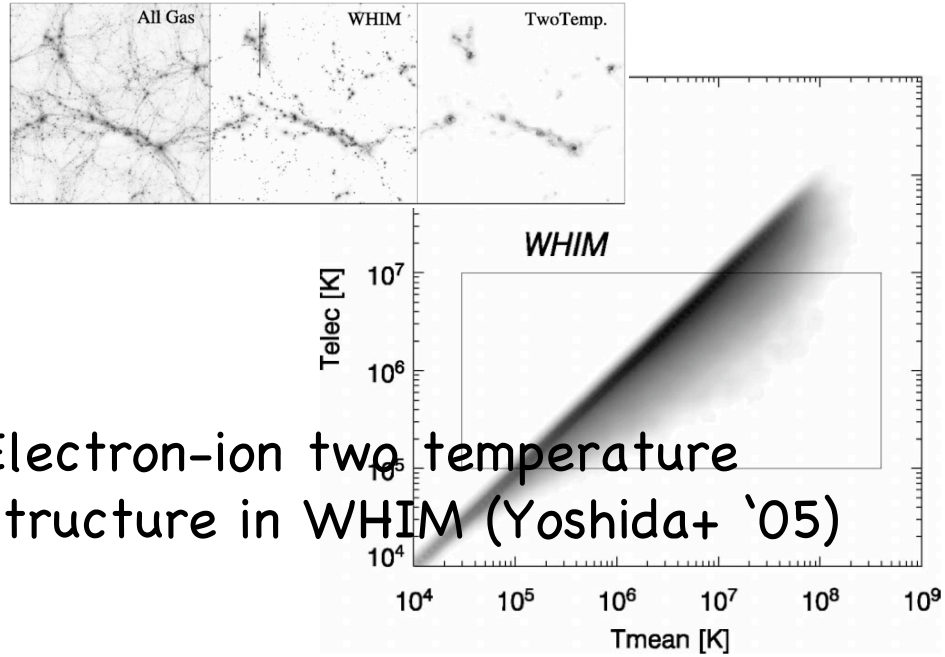


A non-equilibrium ionization state of Ovii in WHIM (Yoshikawa, Sasaki '06)

How significant in ICM in the linked region of the merging cluster?

→3D Gas/DM simulations + non-EQ & 2T calculations

Simultaneously!!

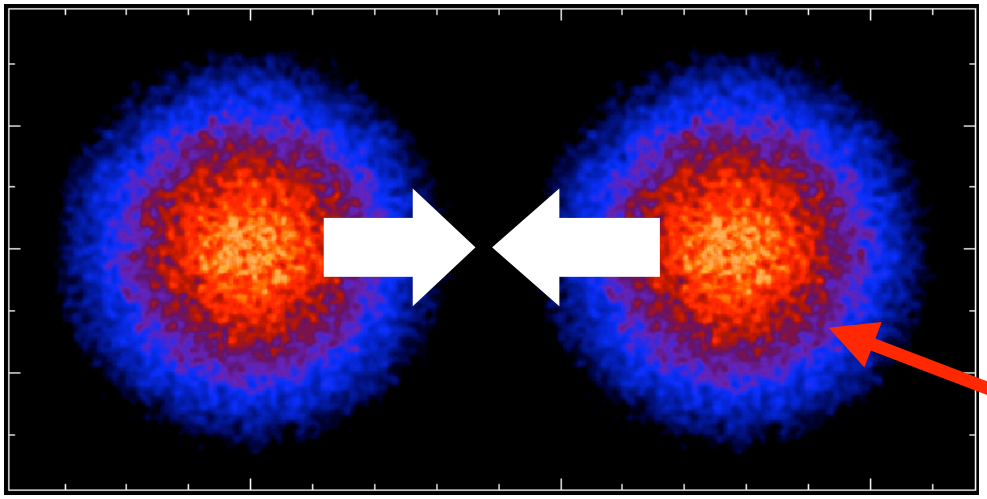


Electron-ion two temperature structure in WHIM (Yoshida+ '05)

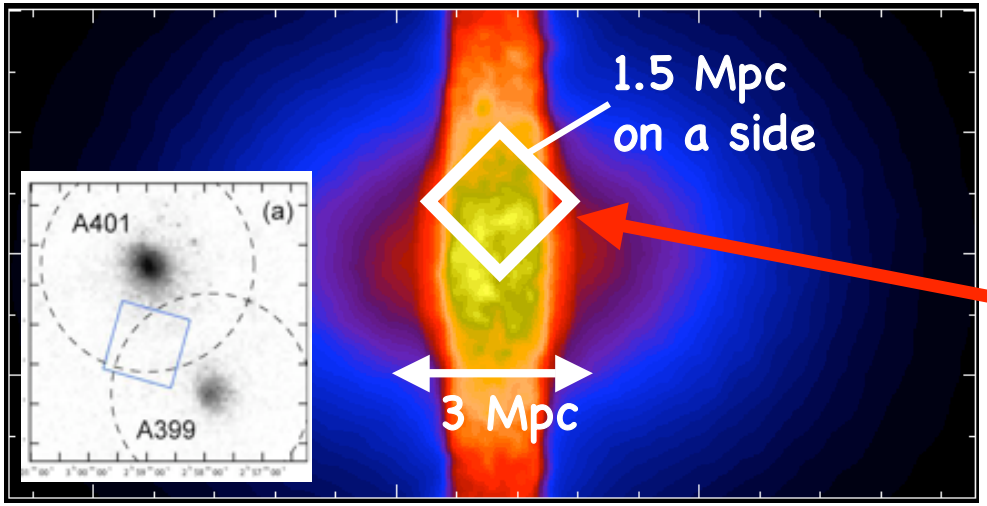
4) Model

Initial

Initial Property	Value
$n_0^{\rm fit}$ ($\times 10^{-3}$ cm^{-3}), $r_c^{\rm fit}$ (Mpc), $\beta^{\rm fit}$	5.00, 0.16, 0.61
$T_{\rm sl}$ (keV) at 0, 0.75, 1.5 Mpc	7.64, 5.00, 3.42



Present



To reproduce the situation of A399/401, …

- 1:1 head-on merger
- face-on view
- Init. ICM distribution
  - Asca: temp. map
    $T(r)=(Tvir/\beta)\exp(-r/r_{vir})$
  - Newton: β-model fit
    $n(r)=n_0\{1+(r/r_c)^2\}^{-3\beta/2}$
  - Hydrostatic Equilibrium
- Init. relative velocity
  - 1050 km/s
  - to reproduce the observed temperature of the linked region by Tsl*

*Tsl: the spectroscopic-like temperature (Mazzotta et al. 2004)

5) Method

- SPH + N-body
  - 10^6 particles for each component
  - h~0.1 Mpc @ the linked region
  - MG+Balsara viscosity
  - FIRST simulator @ CCS, Tsukuba
- Ionization fractions
  - Yoshikawa, Sasaki '06
  - SPEX 1.10/CUBA UVX bkg.
- E-I two-temperature
  - Takizawa '99

FIRST simulator
496 Host CPUs
-3.1Tflops
240 Blade-GRAPEs
-33Tflops
1.6TB memory
22TB storage

$$\frac{df_j}{dt} = \sum_{k=1}^{j-1} S_{j-k,k} f_k - \sum_{i=j+1}^{Z+1} S_{i-j,j} f_j - \alpha_j f_j + \alpha_{j+1} f_{j+1}$$

f_j: ionization fraction of j-1times ionized ion,
Z: atomic number of H, He, C, N, O, Ne, Mg, Si, S, Fe,
$S_{i,j}$: Ionization rate that ion j ejects i electrons,
α_j: Recombination rate for ion j

$$\frac{d\tilde{T}_\mathrm{e}}{dt} = \frac{\tilde{T}_\mathrm{i} - \tilde{T}_\mathrm{e}}{t_\mathrm{ei}} - \frac{\tilde{T}_\mathrm{e}}{u} Q_\mathrm{sh}$$

$$\tilde{T}_\mathrm{i} \equiv T_\mathrm{i}/T \quad \tilde{T}_\mathrm{e} \equiv T_\mathrm{e}/T$$

$$T \equiv (n_\mathrm{e} T_\mathrm{e} + n_\mathrm{i} T_\mathrm{i})/(n_\mathrm{e} + n_\mathrm{i})$$

$$t_\mathrm{ei} = 2 \times 10^8 \ \mathrm{yr} \frac{(T_\mathrm{e}/10^8 \ \mathrm{K})^{3/2}}{(n_\mathrm{i}/10^{-3} \ \mathrm{cm}^{-3})} \cdot \left(\frac{40}{\ln \Lambda}\right)$$

Te, ne: the electron temperature and number density,
Ti, ni: the ion temperature and number density,
T, n: the gas (mean) temperature and number density,
u: the internal energy of the gas,
Qsh: the shock (viscosity) heating rate,
tei: the Coulomb scattering timescale

6) Result 1: Density, Temperature

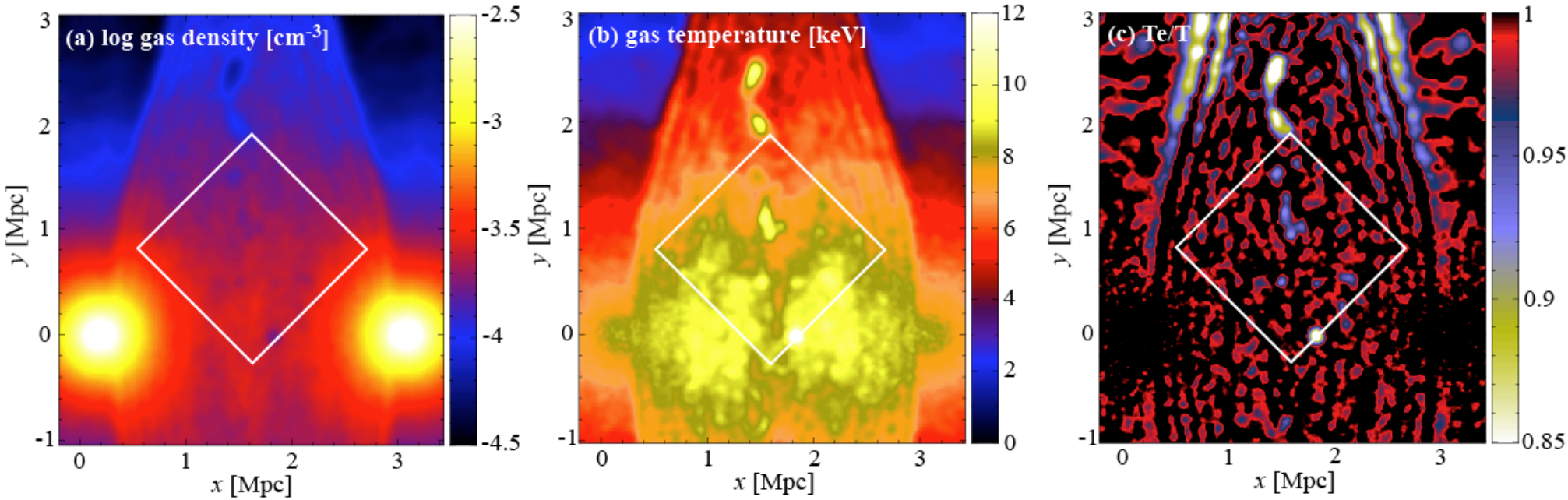


Fig.) The cross sections along the collision axis: the gas density [log cm^{-3}], the gas mean temperature [keV], the electron temperature/the mean temperature

- The gas density ≒ observation (3×10^{-4}cm^{-3}) Agreement
- T (8keV) > Tsl* (6.5keV) ≒ observation (6-7keV) Agreement
- No significant shocks in the linked region

↳ Te is only a few percent lower than T

*Tsl: the spectroscopic-like temperature toward the linked region

7) Result 2: Fe Ionization State

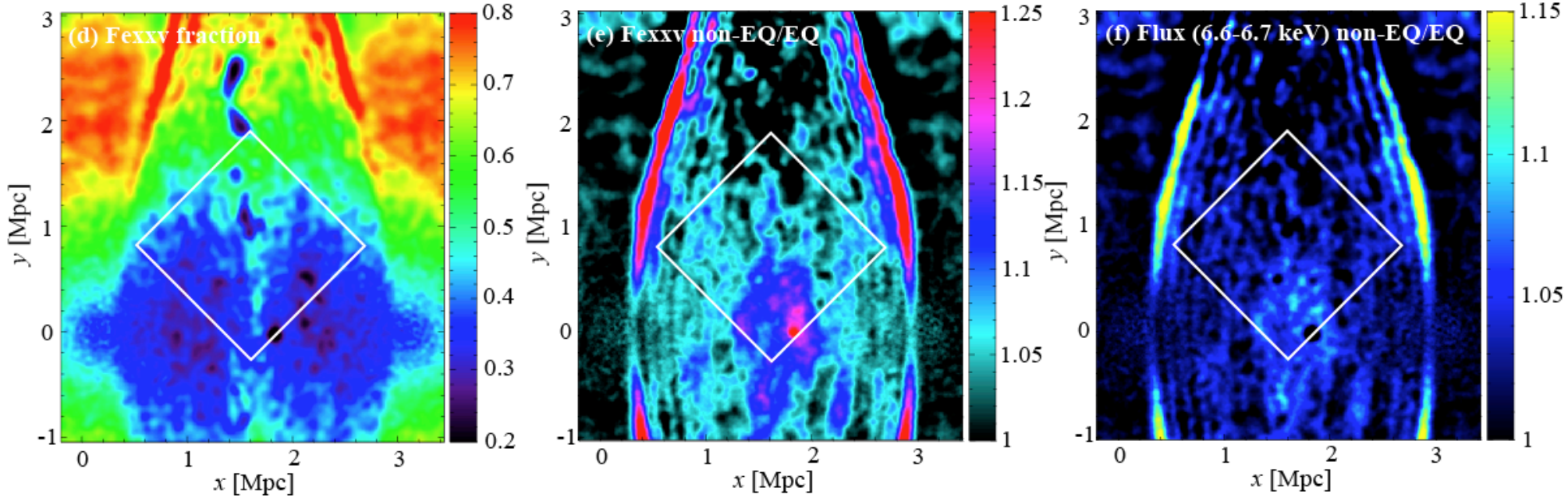


Fig.) The cross sections along the collision axis: the Fexxv fraction, the ratio of the Fexxv fraction relative to that in the equilibrium state, the ratio of the line intensity of 6.6-6.7 keV band relative to that in the equilibrium state.

- **Fexxv (He-like) fraction: 30-60%, the largest fraction**

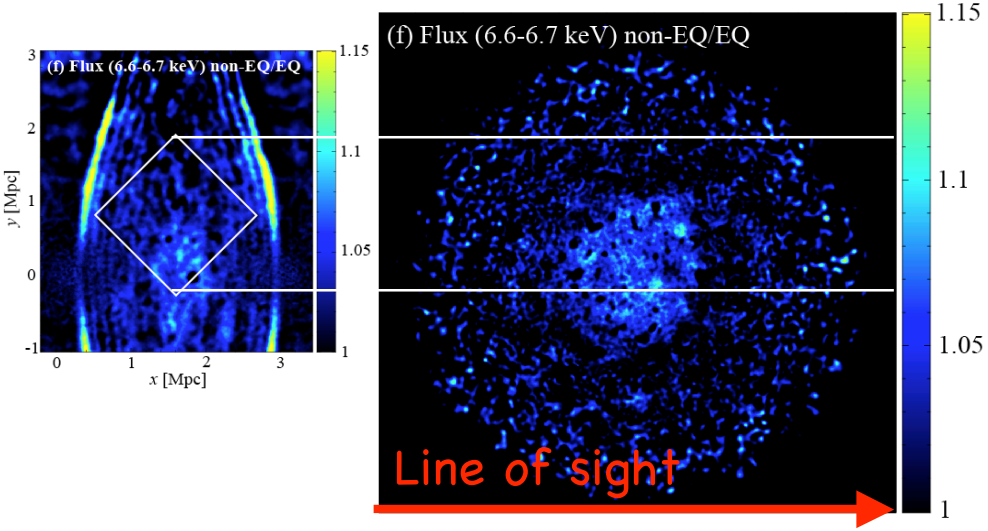
Fexxv is 10-20% larger

6.6-6.7keV band intensity is 5-10% larger

} than that in the equilibrium state (IE & 1T)

★*See discussion 1!!*

8) Result 3: Significance in obs.



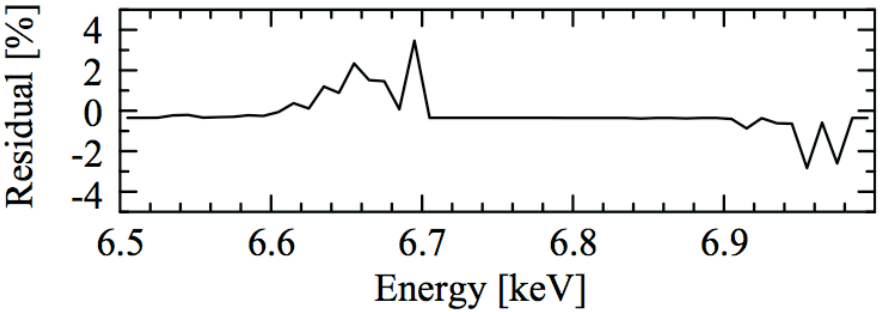


Fig.) The ratio of X-ray spectrum integrated along the line of sight toward the linked region relative to that in the equilibrium state

Fig.) The cross section perpendicular to the collision axis (x=1.6Mpc): the ratio of the line intensity of 6.6-6.7 keV band relative to that in the equilibrium state

- The deviation from the equilibrium state is only significant at around the center of the linked region
- Non-EQ effects on the X-ray spectrum is deluted in integrating along the line of sight

The integrated intensity of 6.6-6.7keV band is only a few percent higher than that in the equilibrium state

★*See discussion 2!!*

9) Discussion 1

- In the linked region, Te increases from 3keV to 8keV according to the adiabatic compression
- Fexxv peaks at 3keV and decreases as Te increases

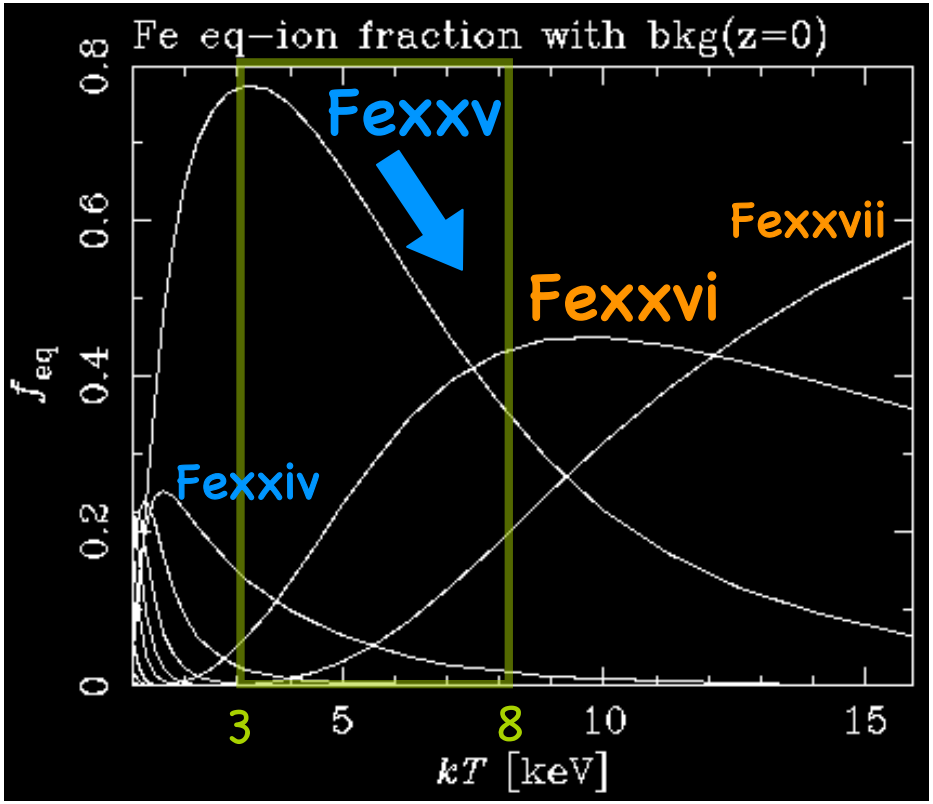


Fig.) ionization fractions of iron in the equilibrium state as a function of Te (=T)

However, Fexxv fraction is higher than that in the equilibrium state because the ionization of Fexxv is not fast enough to catch up with the ionization equilibrium state

Thus, the Fexxv fraction is 10-20% larger than that in the equilibrium state. Meanwhile, the Fexxvi fraction is 5% smaller.

Line emissions by collisional excitation and recombination of Fexxv are stronger, while that by recombination of Fexxvi is dimmer

→

As a result, 6.6-6.7keV band intensity is enhanced (by 5-10%)

10) Discussion 2

- **Metallicity is evaluated from the line intensity, and it would be overestimated in proportion to the intensity enhancement**

The enhancement of a few percent is, however, within the uncertainty of the Suzaku observation

Because there is no enhancement of the number density of galaxies (Sakelliou, Ponman '04), and no noticeable small-scale structures (Fujita+ '08), it may be unlikely that the metallicity is concentrated near the center of the linked region.

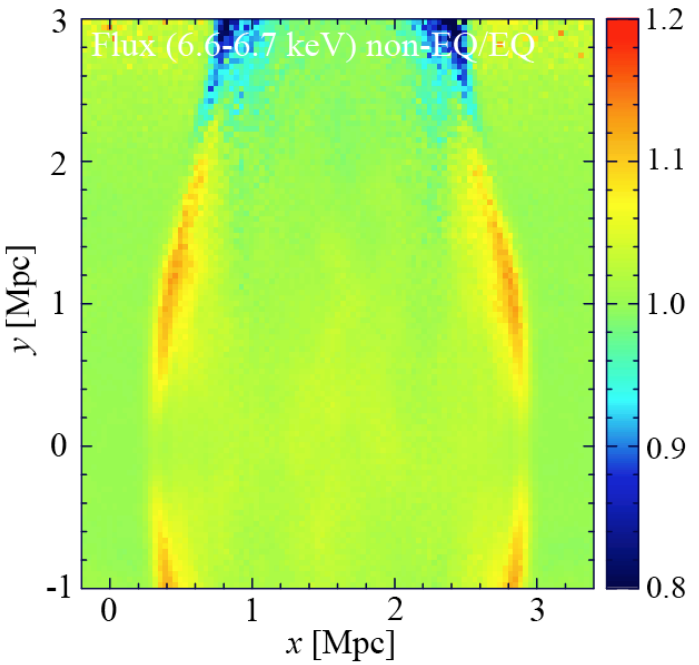


Fig.) The ratio of the intensity of 6.6–6.7 keV band integrated along the line of sight relative to that in the equilibrium state

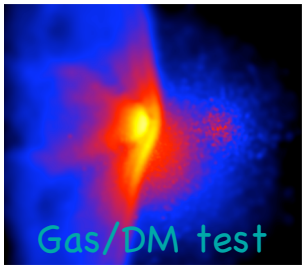
If the metallicity is concentrated near the center of the linked region, the projection effect is insignificant, **though** the deviation of the intensity is 10–20% at the maximum.

Therefore, we may say that 0.2 times the solar metallicity estimated by the observation (Fujita et al. 2008) is valid.

Concluding Remarks

- We investigate a non-equilibrium ionization state and two-temperature structure of the intracluster medium in the linked region of A399/401, using a series of N-body + SPH simulations
- We find in the linked region that:
  1. an ionization fraction of Fe xxv is 10-20 % larger than that in an ionization equilibrium state
  2. the electron temperature is a few percent smaller than the mean temperature of ions and electrons
  3. Fe K emission line intensity integrated along the line of sight is enhanced by a few percent compared with that calculated under the assumptions of the equilibrium state
- HOWEVER, such enhancement is within the uncertainty of the Suzaku observation, suggesting the Suzaku detection of 0.2 times the solar metallicity is not severely affected by a non-EQ ionization state and 2T structure in the region

-future work- We are now doing a systematic study of a non-equilibrium ionization state and two temperature structure in various types (e.g., head-on/off-set, major/minor, ...) of merging clusters. We are also planning a study of the Bullet cluster including radiative cooling.



The simulations in this work were carried out with computational facilities at Center for Computational Sciences in University of Tsukuba. This work was supported in part by Grants-in-Aid for Specially Promoted Research from MEXT in Japan (16002003), and by Japan Society for the Promotion of Science (19840008).